

Institut für Plasmaphysik  
KERNFORSCHUNGSANLAGE JÜLICH  
des Landes Nordrhein-Westfalen

**METHODS FOR THE PRODUCTION OF HIGH DENSITY, HIGH  
TEMPERATURE PLASMAS BY MAGNETIC COMPRESSION  
UNDER CONTROLLED INITIAL CONDITIONS**

von

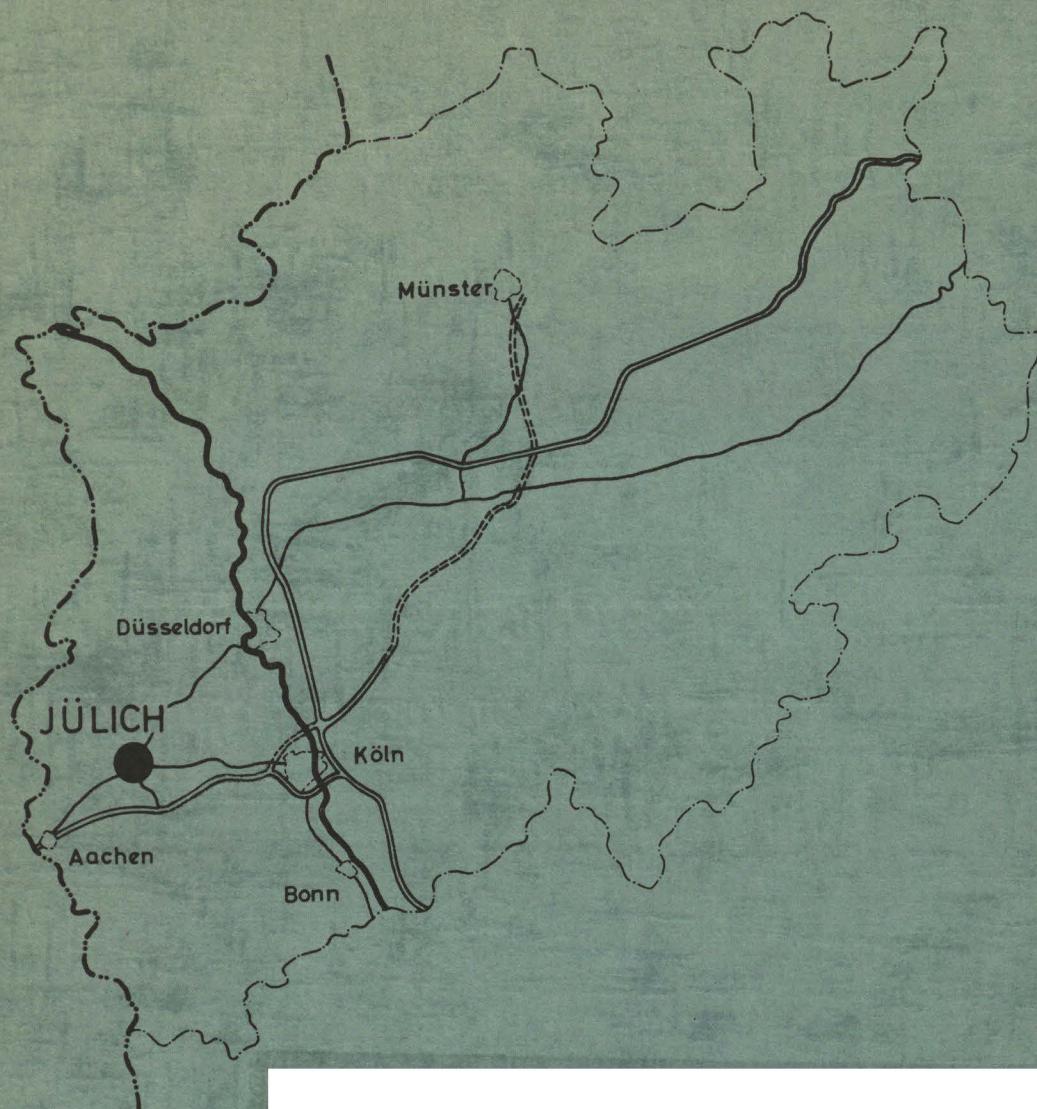
H. L. Jordan

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# METHODS FOR THE PRODUCTION OF HIGH DENSITY, HIGH TEMPERATURE PLASMAS BY MAGNETIC COMPRESSION UNDER CONTROLLED INITIAL CONDITIONS

H. L. Jordan\*

Institut für Plasmaphysik der Kernforschungsanlage Jülich des Landes  
Nordrhein-Westfalen e.V. Jülich/Germany

## ABSTRACT

In earlier magnetic compression experiments, main physical phenomena were observed in the second or later half cycles of the compression field. Plasma conditions at the beginning of the compression were essentially determined by breakdown properties in the previous half-cycle. Uncontrolled values and distributions of internal magnetic fields, rather high amounts of impurities from wall contamination and inhomogeneity of plasma properties were observed.

A general experimental technique has been developed which allows the formation of a plasma with controlled amounts of internal magnetic field, and the subsequent compression of this plasma. The method uses three capacitor banks which can be switched with a high precision consecutively on the same compression coil. As the same compression coil is used in all stages of the experiment, this technique preserves symmetry and can therefore be applied for different field configurations and coil dimensions, in contrast to other methods for preheating.

Measurements on a small scale experiment were made over a large range of parameters and are described in detail in other reports [1, 2, 3, 4] at this conference. The essential results are, that in the preheating phase an almost fully ionized, uniform plasma with low impurity content and controlled amount of internal magnetic field is

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formed. By the subsequent fast compression of this initial plasma, a high density and high temperature plasma is obtained in a fully reproducible way. The ratio  $\beta$  of kinetic pressure to external magnetic pressure can be made small or close to 1. The pilot experiment has proved the effectiveness of the method. Based on the same principles, a larger compression experiment is now under construction at Jülich.

## 1. HEATING OF PLASMA BY MAGNETIC COMPRESSION

Magnetically confined plasmas can be heated by enlarging the strength of the confining field. The external magnetic pressure grows and the plasma is compressed. This method is generally called magnetic compression. Depending on the time elapsed from start to peak compression compared to other characteristic times, such as particle collision times, energy transfer time, transit times for small and large amplitude disturbances through the plasma region, field diffusion time and characteristic times for various types of losses, the temporal and spatial development of the plasma compression differs greatly.

A large number of phenomena have been observed, which show that under very similar external conditions plasmas with greatly differing configuration and distribution of internal magnetic field, with greatly varying degrees of wall contamination, of thermalization and of density distribution can be obtained. Electron and ion temperatures, stability properties, and losses show great variations. As a whole, the physical picture is usually complex and rather confusing. A number of idealized cases can be regarded theoretically, but actual experiments are at best a mixture of these models:

- a) 2-dimensional adiabatic compression of an initially homogeneous thermal plasma with or without internal magnetic field.

Collision and diffusion times are large compared to the compression time, while transit times are small. The plasma can be treated as

collision free and energy transfer to the third degree of freedom of the translational motion can be disregarded.

- b) 3-dimensional adiabatic compression of an initially homogeneous thermal plasma with or without internal magnetic field. Transit times are small compared to compression time, while collision times are comparable. Depending on field diffusion time, the initial ratio  $\beta$  of kinetic energy density of the plasma to the external magnetic energy density is more or less preserved during compression. The final temperature and homogeneity in both cases depend on the compression ratio and the exponent of the adiabatic law, the  $\beta$  of the plasma and on the rate of field diffusion.
- c) Fast (non adiabatic) compression of an initially homogeneous thermal plasma. In this case transit times for small and large amplitude disturbance are comparable to the compression time. Compression waves and in some cases shock waves influence the heating of the plasma. 2- and 3-dimensional cases can again be regarded.
- d) Compression of an initially homogeneous non thermal plasma with or without internal magnetic field, whereby a plasma with given (e.g. singular) non thermal velocity distributions of ions and electrons is compressed either adiabatically or non-adiabatically, two- or three-dimensionally, depending again on the ratios of characteristic times.

The simpler cases can more or less be described by different plasma models, such as collision free models, snow-plow models, one- or two-fluid hydromagnetic models, and kinetic models.

In order to improve the understanding of physical processes and to make theory applicable, experiments should aim at reaching if possible the simplest of the cases mentioned. This means specifically a high degree of homogeneity of all plasma properties, a low percentage of neutrals and impurities, and thermal velocity distributions of ions and electrons, if possible with equal ion and electron temperatures. Initial plasmas

before compression should have a high conductivity, so that a thin sheath is formed which separates for the time of compression the external field from the plasma.

## 2. EXPERIMENTS ON MAGNETIC COMPRESSION

A large number of experiments on the magnetic compression of plasmas have been reported [e.g. 5 - 14]. In these experiments various configurations of the compression field were used, such as magnetic fields produced by straight homogeneous cylindrical coils, mirror and cusp fields, and toroidal fields. While in earlier experiments these fields are applied to an initially cold neutral or weakly ionized gas, some experiments reported lately are performed on initially highly ionized plasmas.

These initial plasmas are either produced outside of the compression region by plasma sources or plasma guns and shot into the compression coil, or are produced by a number of different preheating techniques inside the compression region. In particular high power RF discharges, pinch discharges, oscillating electrodeless ring discharges and reflex discharges were used, as reported e.g. in several contributions to this conference.

In non preheated experiments an oscillating compression field is used, whereby the first half-cycle or some later half-cycle serves as a preheating phase. A common feature of these experiments is the existence of a trapped internal magnetic field, which depending on breakdown conditions and conductivity can reach large values in particular anti-parallel to the external field during the second (or the effective) half-cycle compression. A rather large concentration of impurities is then found in the plasma, which have been detached from the wall of the enclosing tube at the end of the preheating cycle. The amount and the spatial distribution of the trapped internal field is strongly dependent on the initial gas pressure, on the impurity concentration, and on a number of other parameters. Although some of these experiments seem to have produced large mean ion energies of probably thermal origin and relatively quiescent plasmas of high density, the interpretation of the physical

processes underlying is still rather difficult. This is due to the fact that during the preheating cycle an initial plasma is formed, but its physical state is unknown and uncontrolled. Breakdown conditions for the originally neutral or weakly ionized gas depend on the density, on the rate of rise of the external magnetic field, on the value and rate of rise of the induced electric field, and on the initial degree of ionization.

These parameters can be varied by varying gas pressure, voltage and energy content of the capacitor bank, the ratio of internal to external inductance of the experiment, the dimensions of the compression coil, and the power, voltage, and coupling of the preionizing RF-circuit. The common experience shows that the variation of one external parameter changes practically all internal parameters of the plasma in such a way, that a systematic study of plasma properties during the compression and a comparison between different experiments is difficult.

Regarding the possibility of a larger volume compression experiment the first half-cycle preheating is in addition to this uneconomical, as a rather considerable part of the initially stored electric energy is used up by damping in this first half-cycle.

### 3. PREHEATED EXPERIMENTS

Essential progress has been made in a number of preheated experiments. In these experiments magnetic compression and formerly observed second half-cycle phenomena occur already in the first half-cycle and considerably smaller impurity concentrations can be reached. [ 5, 9] Since in earlier experiments the initial state of the plasma before compression was neither known in detail nor too well reproducible, the physical information obtained was again limited.

### 4. MAGNETIC BIAS FIELD EXPERIMENTS

A number of authors [ 9, 10, 11 ] have observed that the most critical parameters for a compression experiment are strength, sign, and spatial distribution of the initially trapped magnetic field. These parameters can



be varied to some extent by the addition of a static magnetic bias field of variable sign and amplitude. Experiments reported on this technique [ 12, 13] have proved the fundamental importance of trapped fields and show characteristic differences in plasma behaviour during compression for the cases of parallel and antiparallel internal field. Under reverse field conditions, high mean ion energies and neutrons from D-D reactions are now observed already in the first compression half-cycle [ 18] . Calculations by Hain [ 15] on the compression of a low  $\beta$  plasma with internal strong parallel or antiparallel fields indicate in the antiparallel case sharp fronts, in the parallel case a more homogeneous radial density distribution. Again a comparison between theory and experiments is difficult, as long as the initial state of the plasma is not sufficiently known.

## 5. PREHEATING UNDER CONTROLLED CONDITIONS

These considerations have led during the past two years at the Plasma Physics Institute, Juelich, Germany, to the development of experimental and diagnostic techniques for the production and subsequent magnetic compression of an almost fully ionized initial plasma with a known and reproducible state.

The method is generally characterized by the use of three capacitor banks, which can be switched with a high precision of timing consecutively on the same compression coil (Fig. 1) :

- a) A slow, or square wave, bank for the generation of a quasistatic initial magnetic bias field.
- b) A high resonance frequency bank for the production of a highly ionized, magnetically isolated plasma.
- c) A larger low inductance bank for the main compression field.

A fourth bank may be necessary for the forming of the boundary layer before the main compression.

A fundamental advantage of this method is, that in contrast to other

methods of preheating and producing bias fields, the same compression coil is used for all stages of the experiment. Shape and symmetry is therefore preserved for all magnetic fields used in sequence.

Some of the construction techniques for these low inductance banks have been described in earlier reports [ 10, 16, 17] .

## 6. PILOT EXPERIMENT

A pilot experiment for the study of this method was constructed by Hintz and Fay . An important contribution to the switching technique was given by Beerwald and Hintz [ 16] . Hintz , Bogen and others have made with this experimental facility extensive studies on the breakdown, formation of the initial plasma and on the subsequent magnetic compression. These compression experiments have been made with Hydrogen, Deuterium, and with added impurities, for a range of initial densities and for different values and polarity of the trapped internal field. Measurements on the breakdown, preheating, and compression phase were made with small steel shielded magnetic probes, time and space resolved spectroscopy in the visible and UV, smear camera photographs and microwave interferometry.

Some results of these measurements are reported at this conference [ 1, 2, 3] and a comparison between these results and theoretical calculations on the dynamic behaviour of the compression of an axially symmetric plasma with trapped internal magnetic field has been made by Kever [ 4] . These calculations use a free particle reflection model, a snow-plow model and an adiabatic model for the description of different phases of the plasma compression.

The general data of this experiment are :

- a) RF preionizing with a 500 Watt, 10 MC/sec generator, capacitively coupled to the discharge tube.
- b) Magnetic bias field up to 3 kGauss produced by a matched square wave pulsed delay line with 100  $\mu$ sec duration and 4  $\mu$ sec rise time.
- c) Preheating discharge with a pulsed oscillating, magnetic field of

5 kGauss maximum amplitude and 0.9 MC/sec frequency, weakly damped.

- d) Main compression field  $\approx$  50 kGauss, 2  $\mu$ sec half period, produced by a bank of 30 x 25 kV, 0.5  $\mu$ F capacitors. Each capacitor is separately switched. The total bank inductance is  $5 \cdot 10^{-9}$  Hy.
- e) Straight and homogeneous single turn cylindrical compression coil of 15 cm length and 4 cm inner diameter. Inside the coil is a closely fitted quartz tube, which contains the gas.

The experiment is operated in the following way:

After the generation of the magnetic bias field, the weakly RF-preionized gas is ionized and preheated by a rapidly oscillating electrodeless ring discharge, induced by switching one or more high resonance frequency capacitors on the compression coil. The gas becomes thereby highly ionized, and in subsequent half-cycles of the preheater discharge further heating and thermalization of the plasma takes place, mainly by the interdiffusion of antiparallel magnetic fields (field mixing). This effect can be shown by magnetic probe measurements, spectroscopic observations and smear camera photographs [ 1] .

The timing of the main compression bank with respect to the firing of the preheater bank has a precision of  $5 \cdot 10^{-8}$  sec. The main compression can thus be made reproducibly in a chosen part of any half-cycle of the preheating discharge. Observations show that the plasma properties are radially inhomogeneous during the first few half-cycles. In later half-cycles (10 and later) the plasma becomes more and more homogeneous and the outer radius expands until the plasma reaches the tube walls. Up to this time the plasma is practically isolated from the walls, due to its inertia, by the oscillating magnetic field, and has a high degree of purity. Spectroscopic measurements give impurity concentrations below 0.05 % at densities around  $10^{16}$  electrons/cc and temperatures of 2-3 eV. At these temperatures and densities, collision and energy transfer times are short compared to the pulse time, so that the plasma can be assumed to be in thermal equilibrium.



Basic conditions for a simple case are therefore fulfilled, the initial plasma is thermal and magnetically isolated from the tube walls for such a length of time, that it becomes radially homogeneous. Density, temperature, and the distribution of the internal magnetic field can be measured as functions of time. By choosing the time of compression, the value and the polarity of the bias field and the initial density, one can realize the compression of a fully ionized, pure, thermal, and almost homogeneous plasma of sufficient conductivity with and without internal field, parallel or antiparallel to the compression field, with known and reproducible initial conditions over a wide range of parameters.

The clearest experimental results are obtained, when the main compression field is applied in later half-cycles [2] of the preheating discharge, when the plasma almost fills the tube. In this case the stray inductance in the coil is a minimum and the coupling of the compression field to the plasma best (Fig. 2).

In summarizing the results of papers [2 - 4], describing the compression phase, it could be shown for the range of parameters used, that

- a) physical phenomena occurring during the compression and containment time are reproducible within the accuracy of measurements,
- b) the compressed plasma is stable and quiescent during the pulse time at least for the case of weak or strong parallel internal field. No instabilities are observed under preheated conditions, while instabilities clearly develop under non-preheated conditions,
- c) a comparison of streak photographs and magnetic probe measurements shows, that magnetic flux inside the plasma is conserved during the implosion and during the compression at least up to current maximum. At current maximum, the period of small amplitude oscillations of the plasma column check with calculated ones for the initial line density, showing conservation of line density. Amplitudes of the radial magnetic field component are small compared to the axial one. These observations indicate high conductivity and exclude small scale instabilities

or turbulence.

- d) Both the initial and the compressed plasma have a very low content of wall impurities. Spectroscopic measurements give impurity concentrations below 0.05 % for both cases.
- e) A high density, high temperature thermal plasma can be produced even in the case of parallel internal field. At line densities of  $1.8 \cdot 10^{17}$  particles/cm in the case of parallel internal field, temperatures  $T_e + T_i$  above  $2 \cdot 10^6$  °K are observed at the relatively high density of  $3 \cdot 10^{17}$  particles/cc. As collision and energy transfer times are short compared to the pulse time of 2  $\mu$ sec, the compressed plasma should become thermalized during the pulse time.
- f) A number of characteristic differences are observed for the cases of strong parallel, weak parallel, and for the case of strong anti-parallel internal field (Figs. 3-5). The parallel case shows a conservation of the spatial distributions during the compression both for weak and strong internal fields. In the case of a strong antiparallel field, a hollow cylinder of high density plasma is initially formed and collapsed. After the first compression, this hollow cylinder first oscillates, compressing and decompressing the reverse field trapped inside. As shown both by magnetic probes and smear pictures, the central hole then suddenly disappears, simultaneously with the reverse trapped field on the axis.
- g) For the parallel field case, implosion times calculated by a snow-plow model with internal magnetic field check with observed ones. Plasma energy calculated from the same model can account for about 2/3 of the plasma energy observed, at current maximum.
- h) In addition to the results stated in papers [2 - 4],  $10^5$  neutrons per pulse are observed at low (50 - 120  $\mu$ ) initial pressures in Deuterium under reverse field conditions. Space resolved Doppler broadening measurements of C V lines both side on and end on indicate a spatially symmetric distribution with mean ion energies  $\approx 1$  KeV. Time resolved line profiles have not yet been obtained. Since both radial and axial

shock waves are observed, it cannot be excluded that the associated velocity distribution is non-thermal.

Hard X-rays appear only at low densities and at breakdown during the preheating phase. The time of appearance depends on the line density. These X-rays can therefore be attributed to highly accelerated electrons striking the walls, which have been produced during the breakdown phase.

## 7. LARGE SCALE EXPERIMENT

For the purpose of the magnetic compression of a larger volume of plasma and for longer containment times a larger energy storage is necessary. In a joint effort between a group at this laboratory (Anger, Bohn, Fay, Friedrich, Hopmann, Jelinek) and the Brown, Boveri Co. Mannheim, a large scale compression experiment with magnetic bias field and controlled preheating is under construction at Juelich. The general data of this experimental facility are for the first stage:

- a) Magnetic bias field 5 kGauss maximum, charging voltage 20 kV, inductance 1  $\mu$ H, 96 x 7.7  $\mu$ F capacitors.
- b) Preheating bank 40 x 0.3  $\mu$ F capacitors max. charging voltage 40 kV.
- c) Main compression bank 384 x 7.7  $\mu$ F capacitors, charging voltage 20 kV, stored energy 600 kJoule.
- d) Compression coil 1 m length, maximal 1.5 m, 10 cm diameter.
- e) Peak field 120 kGauss
- f) Half period 20  $\mu$ sec.

## 8. FURTHER APPLICATIONS

The technique described can be applied to other magnetic field geometries. Experiments on the production of plasma pulses by a plasma gun with an inhomogeneous driving coil are being undertaken at the laboratory along



the same general lines. Studies on the production and compression, on stability and losses of plasmas in cusped geometries should be possible using the same method, but require rather large low inductance capacitor banks.

Although this method has been applied only to fast magnetic compression experiments, it could equally well be applied to slower purely adiabatic compression experiments.

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## CAPTIONS

- Fig. 1           Block diagram of circuit
- Fig. 2           Smear camera picture of preheating discharge  
Initial pressure  $230 \mu D_2$
- Fig. 3           Smear camera picture of plasma compression in the case of strong parallel internal magnetic field  
Initial pressure  $230 \mu D_2$ ,  $B_0 = +2.5$  kGauss
- Fig. 4           Smear camera picture of plasma compression in the case of weak parallel internal magnetic field  
Initial pressure  $300 \mu D_2$ ,  $B_0 < 0.5$  kGauss
- Fig. 5           Smear camera picture of plasma compression in the case of strong antiparallel internal magnetic field  
Initial pressure  $230 \mu D_2$ ,  $B_0 = -2.5$  kGauss

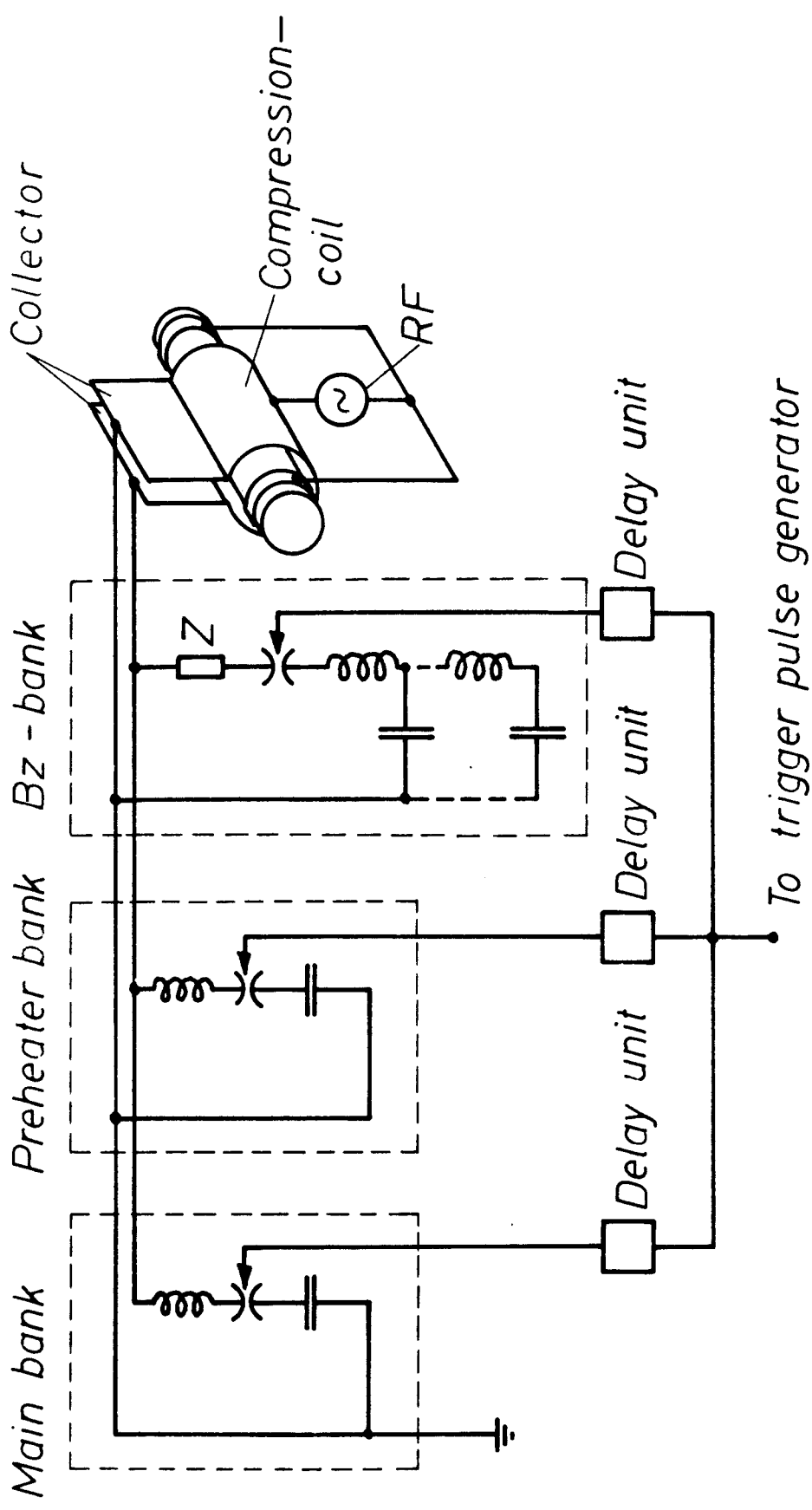
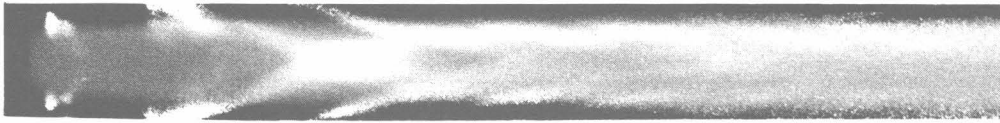


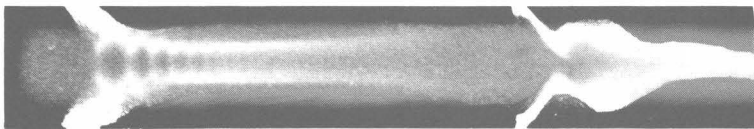
Fig.1 Block diagram of circuit



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Fig. 2

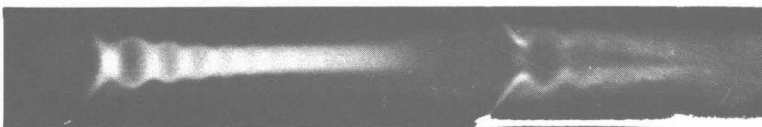
Smear camera picture of preheating discharge  
Initial pressure  $230 \mu\text{D}_2$



1  $\mu$  sec

Fig. 3

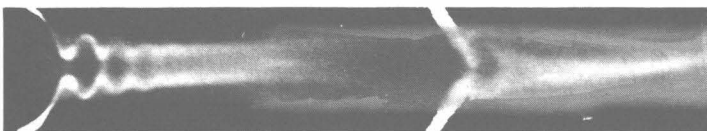
Smear camera picture of plasma compression  
in the case of strong parallel internal  
magnetic field  
Initial pressure  $230 \mu\text{D}_2$ ,  $B_o = + 2.5$  kGauss



1  $\mu$  sec

Fig. 4

Smear camera picture of plasma compression  
in the case of weak parallel internal magnetic  
field  
Initial pressure  $300 \mu\text{D}_2$ ,  $B_o < 0.5$  kGauss



1  $\mu$  sec

Fig. 5

Smear camera picture of plasma compression  
in the case of strong antiparallel internal  
magnetic field  
Initial pressure  $230 \mu\text{D}_2$ ,  $B_o = - 2.5$  kGauss